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Tile Shape Checking of the Beryllium Tiles for the JET ITER-like Wall

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ABSTRACT

The optimisation of the shape of the tiles of the ITER like wall for JET is reviewed with a heat load software which is independent from the one used for the detailed design of the tiles. A particular emphasis is set on the tile edge loads, that are heated by flux tubes penetrating in the toroidal and poloidal gaps. The methodology is presented, along with the detailed description of the analysis for the A2 ICRH limiter. The results are summarised for the other main chamber limiters. The conclusion of the survey is that the edge heating contributions are less than 20%, so that the tile temperature is predominantly the one caused by the main face heating. Plasma operation will not be limited by the tile edges, which is the aim of a safe design.

1. INTRODUCTION

JET is planning the complete replacement of plasma facing components in support of the operation of ITER. Most JET plasma facing components are made of carbon fibre composite; they need to be changed to metal ones, as part of the ITER-Like Wall (ILW) project [1], and in particular to beryllium ones in the main chamber. The position and overall shape of the limiters is not modified with respect to the present ones. Most of the modifications concern the detail geometry of the tiles [2]. The largest beryllium tiles are composed of several blocks and the blocks are castellated.

The tiles are essentially loaded by the heat flux on their radial face (the one facing the plasma). However, tile separations, slices and castellations bring in poloidal and toroidal surfaces. The field line penetration into the gaps is kept minimal by using overlaps with respect to the direction of incoming field lines (the so called “ski ramps”). Complete shadowing of the toroidal and poloidal faces for all situations would necessitate strong overlaps, causing higher incidence angles on the radial faces, and thus higher heat fluxes. The optimum design is the one that ensures the best power exhaust capability, and it is the result of a compromise between shadowing the toroidal and poloidal faces, without introducing overly steep incidence angles on the main face. As a result of this compromise, limited exposure of the internal face of the poloidal and toroidal edges to heat fluxes arises. The heat flux can be high because the incidence angles are usually bigger than on the radial face. This may lead to potential damage to the tile through melting of the beryllium metal [4]. The surface of the tiles has been optimised using a semi-analytical heat flux calculation code [3]. This code computes the heat flux under the assumption of a cylindrical plasma and a cylindrical wall, which only approximates the real geometry as the limiter beams and plasma can have different curvatures.

Because of the complex optimisation scheme, an independent check of the tile surface design was commissioned to reduce the risk, accounting for cases where the real curvatures are introduced. This check was performed with little prior knowledge of the ILW design and with independent modelling tools, thus ensuring the validity of the control. The check consists in calculating the supplementary thermal loads created by the flux tubes penetrating into the gaps by using a parallel heat flux deposition code developed earlier [5–8]. This code basically projects SOL power profiles on the PFC geometry to compute the thermal load and calculates the field line intersection with components to compute the shadows.

This paper describes the concepts and the methodology applied in the heat flux computations in Section 2. Section 3 gives a detailed example of the analysis of the vertical limiter for the A2 ICRH antenna.

2. METHODS

Two inputs are basically required to calculate the heat flux pattern on the tile surface: the geometry of the target surface and the geometry of the magnetic field lines (the magnetic equilibrium). Beside those elements, the required parameters are: scrape off layer power (10 MW) and heat flux decay lengths (10 mm on the outboard side, 20 mm on the inboard side). The magnetic equilibrium comes from PROTEUS [9], which includes a dedicated module able to perform the power balance in the scrape off layer.

The geometry of the components comes from JET CATIA models. The CATIA software is also used to generate the calculation meshes, after removal of the details which are irrelevant to the calculation (Fig. 1). This technique ensure that the shape review is performed on the actual shape that is being sent to the industry, allowing detection of bugs that can have passed from the designer to the draftsmen. Up to three calculation scales are used, namely component scale (typical element size 10 mm), tile scale (typical element size 1 mm) and castellation scale (typical element size 0.1 mm). Accounting for inter-element shadowing requires producing a mesh of the shadowing component, which is usually done with a large element size to avoid excessively long run time. Power deposition is combined with the shadowing mask to obtain the deposition pattern (Figure 2, 3). A more detailed description of the heat flux calculation technique used is described in [10].

A simple thermal estimate combining radial power density with local toroidal and poloidal ones on a semi infinite solid provides the local temperature increase. This is made under the assumption of a 10 s contact. The resulting temperatures are used to sort the cases and identify the most penalising one. The worst-case figure may appear high (up to 4100^{o}C, table 1), but it should be recalled that it is used merely as a gauge to sort the cases on a scale. The whole series can be shifted downward by reducing the power or the contact time.

3. RESULTS

Most of the main chamber assemblies (wide and narrow poloidal limiters, Be and Be-coated inconel inner wall guard limiters, EP2 ICRH lateral protection, private limiter, septum and cross beam, A2 ICRH antenna, LHCD antenna, saddle coil tiles, dump plates) have been analysed. This provides a large variety of cases. There are 12 limiters, 3 calculation scales necessitating typically 10 calculation cases, an average of 2 magnetic equilibria per limiter, up to 10 misaligned situations and some component updates, so that the number of cases is of the order of 10^5 and it is not realistic to calculate all of them in an exhaustive manner. The selection of the most relevant cases was done in the course of the task; 300 cases were deemed sufficient to have a comprehensive assessment of the situation, and to give confidence that the results are reliable.

In order to fit in the space authorised by this publication, the only detailed example presented here is the vertical beam of the A2 ICRH antenna. Another example for the wide poloidal limiter is described in [10]. Tile 6 (counted from the bottom) is selected as the most strongly heated tile in one of the magnetic cases. The peak heat flux on the surface is 10.8MW/m^2, which is already limiting with respect to a 10 second contact (only 6MW/m^2 would be theoretically allowed). At the bottom of the tile, where the heat flux has reduced to 9.2MW/m^2, the poloidal face is wetted over a depth of 1 mm by a 1.8MW/m^2 heat flux. Accounting for the edge heating with respect to the contributions of the radial and poloidal faces, the radial heating at 9.2MW/m^2 contributes to 97% of the temperature increase, and the penetrating heat flux of 1.8MW/m^2 to only 3%. This contribution is small with respect to the typical safety margin used in the design (>20%), so that the side heating appears to be acceptable. In this case, there is no heat flux penetration into the castellation, so that there is no supplementary heating caused by a hot corner effect.

Table 1 lists the results by reverse order of relative heating. The most critical limiter is on a saddle coil, but the heat flux is a front face one and the limitation to this component is not caused by the castellations. It should also be mentioned that saddle coil tiles are secondary limiters, which are less critical than the main poloidal limiters. The second group of four cases are on the inner wall guard limiter, a component challenging to design for power handling within the geometrical and installation constrains. Of these four cases, only the third involves a hot corner, with a contribution of only 10% of the heating. Further cases are similar, and as a whole, the gaps are responsible for a maximum leading edge overheating of 20%, a figure which is acceptable.

The effect of the safety factor on the results was checked in some cases : it remain limited to a few percent and does not change significantly the results.

Misalignment has also been considered : it causes small increases of the radial face heat flux (up to 5%). The heat flux penetration depth can increase noticeably (up to 20%), but as the edge temperature increase is dominated by the radial face heat flux, the reduction of the heat exhaust capability caused by the misalignment remains of the order of the radial flux increase, which is a few percent.

CONCLUSION

The surface heat flux of all the main chamber tiles of JET has been checked for a set of limiter cases, under the assumption of a 10 second contact with 10MW in the scrape off layer. The heat flux was evaluated for the whole limiters, chosen individual tiles and in some cases castellations. The evaluation accounts for the inter-component shadowing, which is partially used by the design to hide high heat flux areas from intense plasma contact. This work was done in the frame of a check of the design of the JET ITER like wall. Roughly 300 situations were analysed, and in some cases, the analysis performed led to minor design modifications.

The additional heating caused by the penetrating field lines is small (generally less than 20%) compared to the main face heat flux. This is an indication that the deviation to the ideal surface caused by the castellations, block based design and tile to tile gaps increases the edge temperature only moderately. Therefore, the design is safe, and will not be limited by local geometry effects.

The operation will be primarily limited by the front face heat flux. The tile surface heat flux will have to be controlled by passive (operation instructions) and/or active monitoring (in situ diagnostics: infrared thermography, spectroscopy) to avoid damaging overheating.

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Limiter & tile	Type of deposition	Total temp	Front Flux	Front %T	Pol flux	Pol length	Pol %T	Tor flux	Tor length	Tor %T
LI saddle coil	Front face	4100	25	100						
IWGL T13	Front face	3960	24	100						
IWGL T13	Castellation	3650	20	90	68	1,2	6	68	0,03	4
IWGL T14	Front face	3470	21	100						
IWGL T14	Front face	3470	21	100						
UO saddle coil	Front face	3370	20.4	100						
UI saddle coil	Front face	3240	19.6	100						
IWGL T13	Tile to tile groove	3140	15	79	7	6	21			
PL Vri T03	Front face	3090	18,7	100						
PL Vri T03	Tile to tile groove	2980	17	94	5	1,3	6			
NPL T23	Front face	2970	18	100						
IWGL T9	Tile to tile groove	2920	14	79	8	4,2	21			
UO saddle coil	Front face	2910	17.6	100						
IWGL T9	Castellation	2820	20	90	9,7	0,5	5	89	0,04	5
NPL T10	Front face	2640	16	100						
IWGL T8	Tile to tile groove	2560	12	78	7,5	4,2	22			
PL VLe T04	Tile to tile groove	2450	14	94	5,3	0,9	6			
IWGL T2	Tile to tile groove	2430	16	86	20	3	14			

Table 1: Synthesis of the power deposition calculation for JET main chamber limiters of the ITER like wall. The first column is the tile identifier. The type of deposition in the second column indicates if the power deposition is on the front face, inside a groove between neighbouring tiles or inside the tile, on a castellation. The following column is the total temperature increase caused by a 10 second contact at 10 MW. Subsequent columns give the heat fluxes for each face (front, poloidal and toroidal), as well as the penetration length for the poloidal and toroidal faces. The "%T" columns give the relative part of the temperature increase caused by a face to the total temperature increase. The temperatures are given in ^{o}C, the heat fluxes in MW.m^{-2} and the lengths in mm.

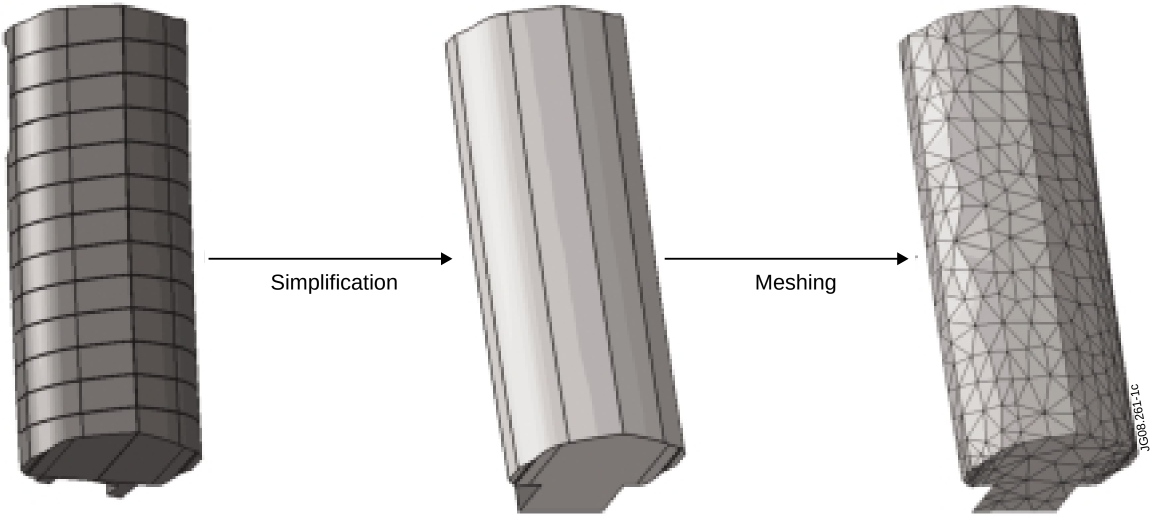


Figure 1: Simplification and meshing of a tile extracted from the vertical beam of the A2 antenna.

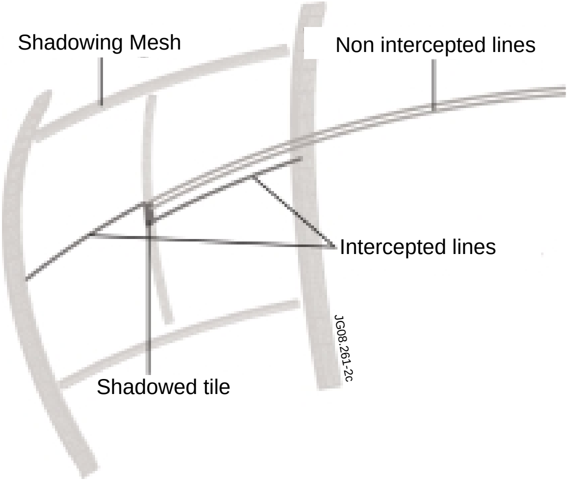
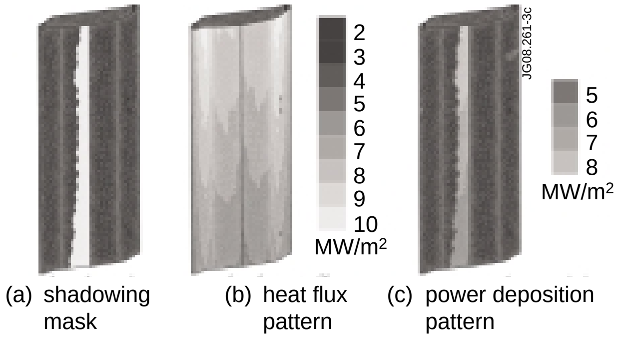


Figure 2: Field line tracing for the shadowing computation.



(a) shadowing mask (b) heat flux pattern (c) power deposition pattern

Figure 3: Heat flux on tile 5 of the vertical beam of the A2 antenna for magnetic case 3610004 (MW/m^2) at the tile scale (simplified surface).

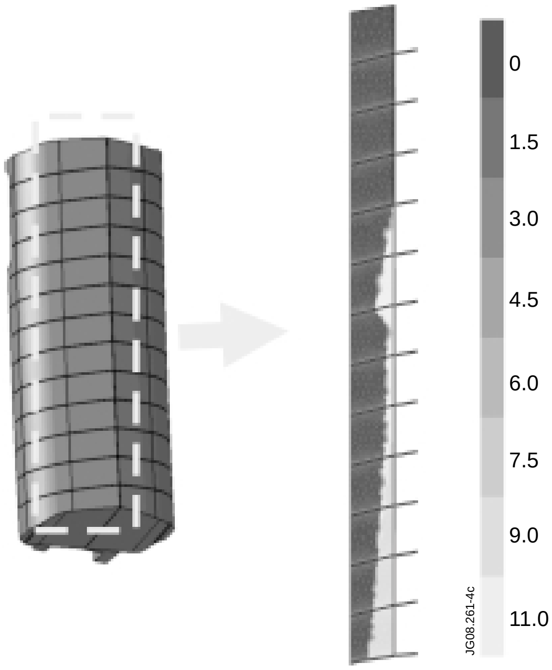


Figure 4: Heat flux on tile 6 of the vertical beam of the A2 antenna for magnetic case 3610004 (MW/m^2) at the castellation scale.